A Search for Supernova-Remnant Masers Toward Unidentified EGRET Sources

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Abstract. Supernova remnants expanding into adjacent molecular clouds are believed to be sites of cosmic ray acceleration and sources of energetic gamma-rays. Under certain environmental conditions, such interactions also give rise to unusual OH masers in which the 1720 MHz satellite line dominates over the more common 1665/7 MHz emission. Motivated by the apparent coincidence of a handful of EGRET sources with OH(1720 MHz) maser-producing supernova remnants, we have carried out a search using the Very Large Array for new OH(1720 MHz) masers within the error regions of 11 unidentified EGRET sources at low Galactic latitude. While a previously known maser associated with an HII region was serendipitously detected, initial results indicate that no new masers were found down to a limiting flux of, typically, 50 mJy. We discuss the implications of this result on the nature of the unidentified Galactic EGRET sources.

MOTIVATION

A search for OH(1720 MHz) maser emission toward unidentified EGRET sources is both theoretically and observationally well-motivated.

- Supernova remnant (SNR) shocks are believed to harbor sites of cosmic ray acceleration and production of high-energy γ rays: Fermi acceleration may produce relativistic protons that interact with ambient nuclei to create π^0, which decay into high-energy γ rays. A nearby molecular cloud can increase the density of target nuclei (e.g., Aharonian et al. 1994). OH maser emission is an unambiguous tracer of the type of interactions likely to produce high-energy γ rays (Claussen et al. 1997; Wardle 1999).
- The positions of γ-ray sources and SNRs on the sky are correlated (e.g., Sturner & Dermer 1995; Esposito et al. 1996), especially for nearby remnants. This correlation has been attributed to the presence of young, rotation-driven pulsars within the SNR, but the alternative hypothesis (that the remnants themselves are the γ-ray sources) has been largely unexplored observationally.
- OH(1720 MHz) maser emission is detected from nearly two dozen Galactic SNR adjacent to molecular clouds (e.g., Frail et al. 1996; Green et al. 1997; Yusef-Zadeh et al. 1999), including four remnants associated with EGRET sources. These sources have hard spectra and do not exhibit significant variability.
- Perhaps coincidentally, SNRs found to contain OH masers and hard low-latitude EGRET sources are both more prevalent in the inner Galaxy. Such a spectral

disparity between inner- and outer-Galaxy EGRET sources would be difficult to explain in a pulsar-origin model.

For these reasons, we chose the satellite line of the hydroxyl radical (OH) at 1720.5 MHz as a tool to uncover remnants that may be obscured by nearby or surrounding molecular clouds.

OH(1720 MHZ) MASER EMISSION

OH(1720 MHz) masers have proven to be unique probes of C-type shocks, the magnetic fields of SNRs behind the shock front, and gas dynamics (Wardle 1999). 1720 MHz line emission is clearly evident in IC443, W28, W44 (Frail et al. 1996) and Sgr A East (Yusef-Zadeh et al. 1996), all of which are coincident with EGRET sources. Three other SNRs possibly associated with EGRET sources, CTA1, Monoceros, and γ-Cygni, apparently do not contain OH masers—the stringent criteria for producing such masers (an X-ray or cosmic ray flux to dissociate H_2O formed in the shock to OH, and molecular gas densities and temperatures appropriate for collisional pumping of the OH; Wardle, Yusef-Zadeh & Geballe 1998) are not often met, even if particle acceleration and γ-ray production are occuring. Indeed, Green et al. 1997 find that only 10% of the remnants they surveyed contain OH masers, most of which belong to the morphological class of radio shell, center-brightened thermal X-ray ("mixed morphology"; Rho & Petre 1998) SNRs. By contrast, four of seven putative EGRET-SNR associations exhibit OH maser emission.

TARGET SELECTION

Source selection was based on the Second EGRET Catalog, its Supplement, and Lamb & Macomb's (1997) catalog of GeV sources. Telescope pointings were based on source coordinates and error circles from the Third Catalog. We used available corollary information for source spectra and variability (Merck et al. 1996; McLaughlin et al. 1996). Consistent with the properties of the existing (postulated) SNR associations, two anticenter and nine inner-Galaxy EGRET sources were selected as targets according to the following criteria:

- visible from the VLA: $\delta \geq -35^\circ$,
- low Galactic latitude: $|b| \leq 10^\circ$,
- evidence of hard spectrum: $\alpha \leq -2.0$ (for $F \propto E^{-\alpha}$), or appearance in GeV source catalog.

Telescope scheduling contraints and the sizes of the EGRET error circles precluded a deep search of the full error region for each target of interest. Our chosen observing strategy (integration time vs. number of pointings) represents a compromise between sensitivity and coverage of the error regions with $\sim 25'$-diameter FOV imaging.

TABLE 1.

Source	l	b	V^*	α/**GeV**†		**Notes****
OH(1720 MHz) Maser Search Targets.						
3EG J0459+3352	170.30	−5.38	0.53	2.2	C	2EG J0506+3424
3EG J0634+0521	206.18	−1.41	0.13	1.9	C	2EG J0635+0521
3EG J1734−3232	355.64	0.15		GeV		GEV J1732−3130
3EG J1809−2328	7.47	−1.99	1.69	2.1/GeV	C	2EG J1811−2338
3EG J1812−1316	16.70	2.39	3.05	2.3/GeV	C	2EG J1813−1229
3EG J1823−1314	17.94	0.14	1.41	2.0/GeV	C	2EG J1825−1307
3EG J1837−0606	25.86	0.40		GeV		GEV J1837−0611
3EG J1903+0550	39.52	−0.05		GeV		GEV J1907+0556
3EG J2021+3716	74.76	0.98	1.40	1.9/GeV	C	2EG J2019+3719
3EG J2033+4118	75.58	0.33		GeV		GEV J2035+4210
3EG J2227+6122‡	106.53	3.18	0.34	2.1/GeV?		2EG J2227+6122
EGRET sources tentatively identified with SNRs.						
3EG J0010+7309	119.92	10.54	1.49	GeV		CTA1
3EG J0617+2238	189.00	3.05	1.52	2.0 GeV		IC443(OH)
GEV J0633+0645	204.83	−0.96		GeV		Monoceros
3EG J1746−2851	0.11	−0.04	1.88	GeV		Sgr A E(OH)
3EG J1800−2338	6.25	−0.18	0.05	1.9/GeV	C	W28(OH)
3EG J1856+0114	34.60	−0.54	1.14	GeV	C	W44(OH)
2EG J2020+4017	78.05	2.08	0.83	2.1/GeV	C	γ-cygni

* Variability index of McLaughlin et al. 1996. Values greater than 1 indicate $\sim 2\sigma$ flux variations on $\sim$ 1 year timescales.

† Spectrum of γ-ray flux, $F \propto E^{-\alpha}$; "GeV" indicates $E_\gamma > 1$ GeV sources listed by Lamb & Macomb (1997; "?" for their low-significance sources).

** "C": confused—source flux and significance may be uncertain. "E": may be extended.

‡ In the time since our observations were made, X-ray and radio counterparts to 3EG J2227+6122 have been proposed (Halpern et al. 2001) that suggest a pulsar origin.

SUMMARY OF OBSERVATIONS

The 27 antennas of the NRAO Very Large Array were used in the CnD configuration. Two IF pairs measured the right and left circular polarizations simultaneously, with 128 channels for each IF spanning a bandwidth of 1.5625 MHz. The IF pairs were centered at $v = \pm 80$ km s^{-1}, yielding velocity coverage of ± 216 km s^{-1} when the IFs were combined. Dwell times on each position were typically 10–12 minutes.

The spectroscopic interferometer data were reduced using standard procedures from the AIPS software package (Greisen 2000). A continuum spectrum was fit and subtracted from each channel; the channels were then imaged, and statistics for pixel intensities were formed. We searched for excesses in the normally-distributed noise over and above a false-alarm probability of one pixel exceeding threshold, given the number of channels and pixels (roughly 6σ). In addition to searching for peaks in single channels, we used the SERCH prodecure within AIPS to search for line profiles spread across 2,

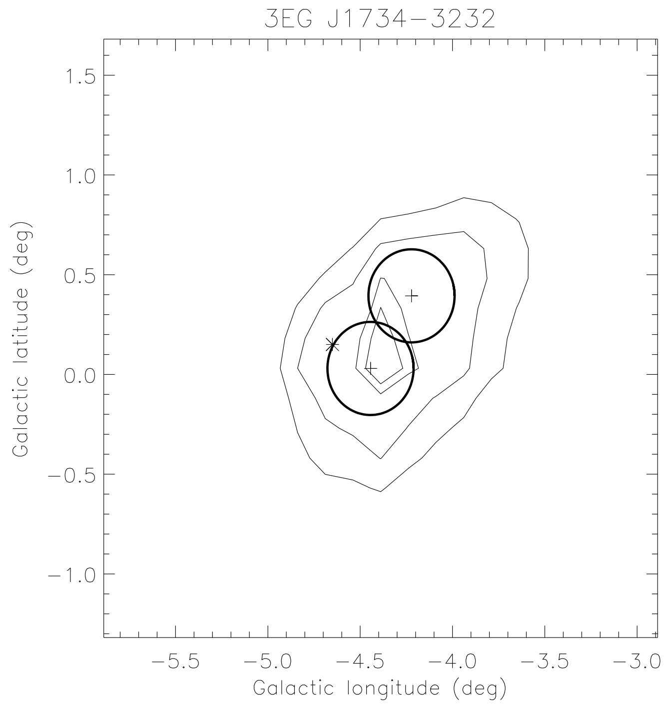

FIGURE 1. Contours of the 3EG likelihood test statistic (Hartman et al. 1999) with two VLA fields-of-view superposed. The asterisk indicates the position of a well-known HII region/OH maser.

3, and 4 channels, to increase sensitivity to weak line emission.

We observed the maser-producing remnant W28 as a test source: its two brightest maser spots were readily detected in a very short (30 sec) integration.

RESULTS

No new OH(1720 MHz) masers were detected in our survey, to a limiting flux of roughly 50 mJy for the inner-Galaxy pointings, and 35 mJy for the two anti-center pointings. Green et al. (1997) show (their Fig. 4) that just two of the 119 OH masers from 17 SNRs have measured flux below 40 mJy, which suggests that our search is sensitive to maser emission out to distances comparable to those of the ~ 160 remnants that have been surveyed for masers to date, i.e., better than half of all cataloged SNRs, and for distances of at least several kpc.

We detected, serendipitously, line emission from the well-known hydroxyl maser and HII region Maser 355.34+00.14 (in which the main OH lines at 1665 and 1667 MHz are not suppressed) as an unresolved source at position RAJ 17:33:28.9, DecJ -32:47:49, near the edge of one FOV (Fig. 1). The 1720 MHz line flux was 65 ± 18 mJy. Higher-resolution observations (Forster & Caswell 1999) distinguish a dozen maser spots with 1665 MHz line flux up to 17 Jy and LSR radial velocity ~ 20 km s^{-1}. The HII region is unlikely to be associated with the EGRET source.

CONCLUSIONS

The incompleteness of our survey, both in areal coverage of EGRET error regions and, to a lesser extent, in sensitivity, makes it impossible to draw firm conclusions about possible associations of unidentified EGRET sources with supernova remnants driving cosmic-ray acceleration and high-energy γ-ray emission. Nevertheless, and despite our present null result, continuing multiwavelength follow-up observations of the unidentified EGRET sources are bringing to light previously unknown supernova remnants that are apparently associated with the γ-ray sources—see, in particular, Combi, Romero & Benaglia (1998) for 2EGS J1703$-$6302 (beyond the VLA's southern limit), and Combi et al. (2001) for three EGRET sources near $(\ell, b) = (6^\circ, -12^\circ)$. The remnants they find are nearby, large, shell-like, and have low surface brightness, and they do appear to abut against (low-density) molecular clouds. If such associations are borne out by future work and found to be common, the apparent absence of OH(1720 MHz) maser emission suggested by our survey may be attributable to the narrow range of environmental conditions under which such emission is expected to arise (Green et al. 1997; Wardle 1999).

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REFERENCES

1. Aharonian, F. A., Drury, L. O'C., and Völk, H. J., *Astron. & Astrophys.* **285**, 645–647 (1994)
2. Claussen, M. J., et al. *Astrophys. J.* **489**, 143–159 (1997)
3. Combi, J. A., Romero, G. E., and Benaglia, P., *Astron. & Astrophys. Letters* **333**, 91–94 (1998)
4. Combi, J. A., et al., *Astron. & Astrophys.*, submitted `astro-ph/0103047` (2001)
5. Esposito, J. A., et al., *Astrophys. J.* **461**, 820–827 (1996)
6. Forster, J. R., and Caswell, J. L., *Astron. & Astrophys. Suppl. Ser.* **137**, 43–49
7. Frail, D. A., et al., *Astron. J.* **111**, 1651–1659 (1996)
8. Green, A. J., et al., *Astron. J.* **114**, 2058–2067 (1997)
9. Greisen, E. (ed.), *AIPS Cookbook*, NRAO, `www.cv.nrao.edu/aips/cook.html` (2000)
10. Halpern, J., et al., *Astrophys. J. Letters* **552**, 125–128, (2001)
11. Hartman, R. C., et al., *Astrophys. J. Suppl. Ser.* **123**, 79–202 (1999)
12. Lamb, R. C., and Macomb, D. J., *Astrophys. J.* **488**, 872–880 (1997)
13. McLaughlin, M. A., et al., *Astrophys. J.* **473**, 763–772 (1996)
14. Merck, M., et al., *Astron. & Astrophys. Suppl. Ser.* **120**, 465–469 (1996)
15. Rho, J., and Petre, R., *Astrophys. J. Letters* **503**, 167–170 (1998)
16. Sturner, S. J., and Dermer, C. D., *Astron. & Astrophys. Letters* **293**, 17–20 (1995)
17. Yusef-Zadeh, F., et al., *Astrophys. J. Letters* **466**, 25–29 (1996)
18. Yusef-Zadeh, F., et al., *Astrophys. J.* **527**, 172–179 (1999)
19. Wardle, M., Yusef-Zadeh, F. and Geballe, R. R., `astro-ph/9804146` (1998)
20. Wardle, M., *Astrophys. J. Letters* **525**, 101–104 (1999)